Behind the Setting of Vision Standards for Aircraft Maintenance Inspection

Bettina L. Beard*

Willa A. Hisle

Jing Xing

Albert J. Ahumada

Phase I Report
15 October 2002

For

William K. Krebs, Ph.D.
Aviation Maintenance Human Factors Program Manager, AAR-100
800 Independence Avenue, S.W.
Washington, D.C. 20591

* Correspondence: tlbeard@mail.arc.nasa.gov; NASA Ames Research Center, Mail Stop 262-4, Moffett Field, CA 94035-1000

Table of Contents

1.0 Introduction

Effective aircraft maintenance inspection requires non-destructive inspection and testing (NDI/NDT) personnel to be experienced, skilled, and able. The present certification and qualification process requires applicants to pass written and practical examinations in order to demonstrate that they are qualified to carry out specific NDT methods. Currently no general standard exists in the aviation industry for the visual qualifications of inspectors; however, the various aircraft maintenance facilities have developed their own, unique vision qualification programs. This highlights the need for a uniform and universally accepted set of vision standards that would apply to all aircraft NDI/NDT personnel.

This report was commissioned by the Federal Aviation Administration (FAA) to partially fulfill FAA Aviation Maintenance Requirement 193, which calls for *Vision Testing Requirements for Certain Persons Maintaining and Inspecting Aircraft and Aircraft Components*. In collaboration with the FAA, NASA has proposed a research plan designed to specify visual needs in relation to specific occupational tasks of aviation maintenance workers and inspectors. As a first step this literature review is being performed to identify and summarize published research relevant to setting occupational vision standards for NDI/NDT personnel.

The following review is a compilation of a text and WEB-based search for occupational vision requirements, knowledge gained from site visits to major aircraft maintenance facilities, relevant information from technical, mechanical, and inspection textbooks, the FAA maintenance human factors web-site[1], and the human vision literature. A principal intent of this literature review is to gather current knowledge about aircraft inspection and human vision, combined with current vision standards required for various other occupations, in preparation for establishing vision standards for specific NDI and visual inspection tasks.

One question that arises is whether standards used in other "Materials Evaluation" occupations can be borrowed for aircraft inspection. Certification programs including vision requirements have been written in the military (MILSTD-410), the naval nuclear program (NAVSEA 250-1500), and for welders (CSWIP). Here we will discuss such standards and their applicability to the vision demands in aircraft inspection.

Optimally, this literature review would follow a thorough vision task analysis for NDI and visual inspection. Although task analysis and descriptions have been performed on aircraft maintenance inspection, (e.g., Drury, Prabhu & Gramapadhye, 1990; Gramopadhye & Kelkar, 1999) these analyses have not focused on the role of visual processes. Within these analyses general observations have been made such as "Reading calipers may be difficult in darkened rooms," or "All defects have low contrast." Without question a more detailed analysis is needed to verify visual task demands.

[1] http://hfskyway.faa.gov

Therefore, the list of visual functions described below is not based on a rigorously obtained taxonomy, but instead on observations made by the authors during site visits.

This report is divided into four main sections. The first section describes the FAA requirement calling for vision standards for NDI/NDT inspectors. We then discuss NDI/NDT basic training, tasks and visual needs and provide an overview of field observations taken by the authors of this report. Section 2.0 excerpts the visual perception literature as it pertains to setting visual requirements. It will be shown that the tools to predict real-world performance are just now reaching maturity. This section also outlines current vision standards for some vision-intensive occupations[2] and whether these standards were empirically derived, based on expert opinion, or borrowed from other occupations. We then discuss to what extent these standards can be applied to aviation maintenance inspection. In Section 3.0 recommendations are provided for vision standards that specifically relate to the vision needs of NDI/NDT inspectors. We conclude that current vision standards written for other occupations cannot be directly adopted when writing aircraft inspection vision standards since the tasks performed by different occupations differ substantially from aviation maintenance inspection tasks. Additionally, the majority of occupational vision standards are not empirically substantiated, and appear to be arbitrarily decided.

1.1 Background

FAA Requirement 193 states that the Project, at a minimum, will determine standards for near visual acuity, distance visual acuity, and color perception for aircraft maintenance inspectors. In a 2001 FAA Advisory Circular (AC), recommendations are made for examination guidelines for the vision of NDI personnel. It is stated that near vision in at least one eye must be 20/25 and distance vision in at least one eye must be 20/50 (both near and far requirements may be with corrected or uncorrected vision), examinations must not be spaced longer than 2 years, and color vision guidelines state that the inspector must: “distinguish and differentiate between colors necessary for the inspection method for which evidence of qualification is sought.”

The 2001 AC previously mentioned was specifically written to address the vision standards for radiographic, magnetic particle, ultrasonic, liquid penetrant, and eddy current imaging techniques. In conjunction with the FAA, NASA proposes to expand these recommendations to include the two most common inspection techniques, visual and borescope inspections.

Many employers assume that the correction of a worker’s refractive error alone is adequate to ensure safe and effective performance on visually demanding tasks. The FAA is interested in developing a performance-based vision standard relevant to all NDI/NDT techniques. The newly formed standards would reflect the actual visual needs for specific tasks performed by the inspector. NASA has proposed a research plan designed to specify visual needs in relation to specific occupational tasks. The proposed

[2] For a more thorough review of published occupational vision standards see the Association of Optometrists (the AOP is based in London) Vision Standards Handbook which can be obtained from http://www.assoc-optometrists.org/.

research will establish empirically sound standards for visual acuity and color vision; additionally, a broader array of visual parameters may be included if it is determined that they are necessary for adequate task performance. Example parameters include, but are not limited to, depth perception/stereo acuity, peripheral vision and contrast sensitivity.

1.2 The Use of Vision in Aircraft Maintenance Inspection

Aircraft inspection is a complex process, requiring many tasks, skills, and procedures. Some tasks are performed in the safe environment of a maintenance workshop facility while others are performed amid potentially hazardous ramp operations. Vision is a fundamental component of effective aircraft maintenance inspection.[3] Not only does good vision ensure that inspectors can better detect airframe and engine component flaws, but good vision is imperative in keeping an inspector and coworkers out of harms way.

Visual inspection (AC 43-13-1B) represents approximately 80% of all aviation maintenance inspection tasks (Goranson & Rogers, 1983). Its main purpose is the detection of discontinuities[4] such as cracks[5] and corrosion[6] within the airframe and powerplant regions of the aircraft. Other visually detectable defects include component wear, chafed electrical wiring, delamination of composites, buckled or bulging skin, and damage due to the environment, accidents, overheating, and lightning strikes.

Significant cracks and corrosion are often subtle or not visible to the naked eye and for this reason inspectors often use visual aids, such as bright flashlights, mirrors, Laroscopes, and magnifying glasses, to increase defect visibility. Borescopes are regularly used to examine inaccessible areas such as the interior of aircraft engines or hidden airframe sections (AC-43-13-1B). Using the borescope, inspectors search for structural defects such as pitting, scoring, tool marks, cracked cylinders, and seal and gasket irregularities.

Additional nondestructive methods of inspection include radiographic, magnetic particle, ultrasonic, dye penetrant, and eddy current inspection. These methods allow subtle or invisible-to-the-naked-eye defects to be detected. There are references that describe these procedures in detail (e.g., Hellier, 2001).

---

[3] Although vision is important, so too are other cognitive factors such as attention. In addition, inspectors are knowledgeable about individual components as well as the overall aircraft being inspected, thus they possess the background to properly locate, identify, and evaluate aircraft defects.

[4] A discontinuity may be defined as "spatially sharp departures from material homogeneity and continuity inside a component at any level of magnification" (Hellier, 2001).

[5] A crack may be defined as "A planar breach in continuity in a material" (Hellier, 2001). They are typically caused by two surfaces being overlaid at a boundary.

[6] Corrosion may be defined as "the electrochemical degradation of metallic materials". (Hellier, 2001).

1.3 Site Visits: Interviews and Field Observations

This literature review was conducted in association with aviation industry partners to ensure its applicability to the setting of vision standards for maintenance inspectors. NDI inspectors and training supervisors were interviewed. Likewise, field observations of experienced inspectors were made, suggesting a number of visual processes that appear to be relevant to NDI and visual inspection. We were able to observe visual inspections, borescope and ultrasonic procedures in addition to the results from florescent penetrant, eddy current, and X-ray procedures.

This first-hand exposure made it apparent that effective inspectors use certain tricks-of-the-trade. For example, rather than scan an entire area, an inspector may look at specific areas known to develop defects, based on his or her knowledge of the structure. Inspectors also know that in order to detect cracks or rough surfaces caused by corrosion, they often must direct a flashlight beam at an angle to the surface being inspected rather than aiming it directly at the surface area. Throughout the following review, we will draw upon these site visits to apply the literature-based knowledge.

2.0 Human Visual Processing, Vision Standards, and Relationship to Maintenance Inspection

How will current vision research and our knowledge of human visual processing provide insight into developing standards for aircraft maintenance inspection tasks? This section focuses on laboratory data collected using real-world visual images because we wish to capture the complexity of the inspection task. In addition, we will discuss the background behind vision standards in other occupations and their applicability to maintenance inspection.

Section 2.0 is organized into five main sections. The first three sections describe psychophysical research related to classical vision requirements; i.e., color vision, near and distance acuity, and peripheral vision. The remaining sections describe research related to visual processes that have not classically been included in occupational vision requirements, but that do *appear* to relate highly to specific tasks performed during aircraft inspection.[7]

2.1 Color Discrimination

2.1.1 Relevant Terms and Basics

Color discrimination is defined as the ability to differentiate between shades of a color or the difference between two or more colors when luminance has been equated or randomized. The factors that influence color discrimination have been described thoroughly (e.g., Kaufman, 1974; Schiff, 1980; Sekuler & Blake, 1990); these sources were used to compile the brief summary of human color vision within this sub-section.

---

[7] Although we have dissected the mechanisms of visual perception into separate processes (e.g., color discrimination, contrast perception, …), perception is an amalgam of these processes working in harmony.

The human retina (a neuro-membrane lining the inside back of the eye) is made up of receptors called rods and cones. When only the rods, densest outside the central retina or macular area, are functioning (i.e., when viewing at low luminance levels), colors are not visible. Cones, densest in the central retina, provide the perception of color.

Humans with normal color vision are traditionally regarded as having three cone types, supporting trichromacy, the ability to match colors with three primaries. As shown in the spectral sensitivity curves in Figure 1, each cone contains a photopigment whose sensitivity peaks at either short, medium, or long wavelengths (e.g., blue, green, or red).

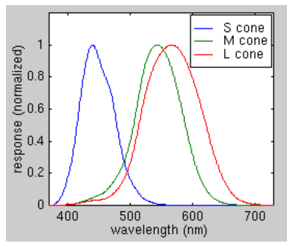

Figure 1. Cone sensitivity plot.

Individuals with inherited color-vision defects have either the complete loss of a photopigment (dichromacy), or a shift in the peak sensitivity of one of the photopigments (anomalous trichromacy), resulting in the decreased ability to discriminate between two colors such as red and green. Approximately 8% of the men and 0.5% of the women of the world are born with some form of color vision deficit, or "colorblindness" (Amos, 1998).

The Ishihara color test is one of several standard color vision tests given by optometrists and ophthalmologists for general and occupational color vision screening. Figure 2(a) shows one of several Ishihara plates. To appreciate how an individual with a color deficit perceives color, the appearance of an Ishihara plate is simulated for three types of dichromats in Figure 2b-d.

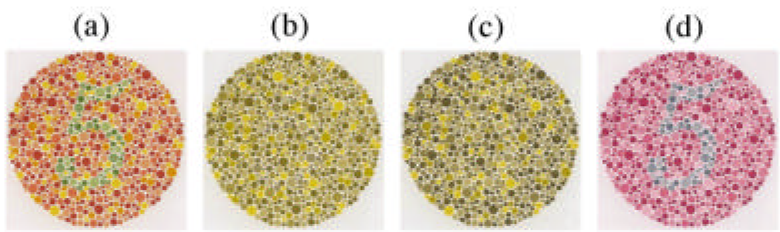

Figure 2. Ishihara Plates. (a) Those with normal color vision should perceive the number "5" embedded in the plate. (b-d) These images are simulations of three types of dichromacy; (b) deuteranope, (c) protanope, and (d) tritanope. Ishihara plates do not measure the severity of color vision loss.

As can be seen in the example above, dichromats have severe color-vision deficits; however, they account for only ~1% of all individuals with a color-vision deficit. The remaining 99% of individuals with an inherited color-vision defect are anomalous trichromats, being either protanomalous (red weak) or deuteranomalous (green weak). The majority of all color defectives are deuteranomalous, with 5% of all males and 0.25% of all females showing this type of deficit (Cline, Hofstetter & Griffin, 1989). The ability to discriminate colors for these two groups can range from almost normal to almost dichromatic. In general, although protanomalous and deuteranomalous people have some difficulty doing tasks that require color vision, many are unaware that their color perception is not normal (Amos, 1998). Some color-anomalous individuals perform better than their color normal peers at certain job tasks. One example from the military is that they may be less confused by camouflaging colors.

Possibly as many individuals have acquired color-vision defects as those with hereditary defects. Most color vision tests screen for red-green color defects, which are the most common hereditary color defect, whereas the majority of acquired color-vision defects are blue-yellow. Acquired defects are most often associated with ocular and systemic disorders such as age-related yellowing of the crystalline lens (cataract), glaucoma, diabetic retinopathy or hypertensive retinopathy. Additionally, many drugs have been documented to induce changes in color perception; examples include tranquilizers, antibiotics, chemotherapeutic drugs, cardiovascular drugs and anti-malarials, which are now often used to treat chronic inflammatory diseases such as lupus (Amos, 1998). Environmentally induced forms of color weakness also exist. Exposure to certain toxic gases (Kilburn, 2000; Dick *et al.*, 2000) and industrial chemicals (Gobba & Cavalleri, 2000; Cavalleri, Gobba, Nicali & Fiocchi, 2000) can induce color vision loss[8]. It is important to monitor color vision loss at each ophthalmological exam, and not assume that color vision is an unchanging ability.

2.1.2 Color Discrimination: Real-world Performance Literature, Vision Standards, and Relevance to Aircraft Maintenance Inspection

There is psychophysical evidence showing that humans have a high sensitivity to color in natural scenes (Chaparro, Stromeyer, Huang, Kronauer, & Eskew, 1993). Color helps us to segment (Gegenfurtner & Rieger, 2000) and to selectively attend to particular aspects of the scene (Deco & ,Zihl, 2001; Parkhurst, Law, & Niebur, 2002).

There has been a great deal of research done on the effects of color deficiencies on air traffic controller (ATC) job performance. Many of the earlier studies involved a small number of color defectives, and typically the experience level of the color defects and normals were not equated. Recently large subject pools of color weak individuals without ATC experience have been tested (Mertens, 1990; Mertens & Milburn, 1992a,b; Mertens & Milburn, 1996; Mertens *et al.*, 2000). Typically subjects are tested on simulated ATC tasks such as color coding of flight progress strips, identifying aircraft lights, and reading color weather radars. The results from these studies suggest that protanopes (Adams & Tague, 1985) and deuteranopes (Kuyk *et al.*, 1992, 1993) are often unable to adequately perform ATC tasks.

The use of certain colors can slow down object detection or discrimination speed for ATC-related object detection (Mertens *et al.*, 1992b) and general text readability (Legge *et al.*, 1990) in color weak individuals. The potential for an adverse interaction of color-coding with color deficiency must always be considered.

---

[8] For example, toluene exposure in rubber workers, PCE exposed dry-cleaners, and exposure to paint solvents or formaldehyde exposures during home renovations.

The performance of individuals with color deficits on discrimination and detection tasks has been studied in several other occupations. In the medical realm physicians with color weaknesses may have difficulty interpreting lab tests, evaluating the color of bodily fluids (Iserson , 2001), or recognizing blood in body fluids (Spalding, 1997, 1999; Reiss, 1993; Reiss, Lebowitz, Forman, & Wormse, 2001). Task accuracy and speed using computer displays are significantly affected by color vision deficits in patients with macular degeneration (Scott, Feuer, & Jacko, 2002).

Although a color vision deficiency can be potentially handicapping, color vision and thus color vision deficits have been found to be minor factors in visual search performance at sea (Donderi; 1994) and in automobile driving performance (Owsley & McGwin, 1999). One reason that color may not be the salient variable for some tasks is that color is often redundant with other salient determiners of attention such as luminance and orientation (Parkhurst, Law, & Niebur, 2002).

Since many airframe and engine defects are identifiable by their color, the correct identification of colors may be very important for efficient aircraft inspection. Consistent with the psychophysical literature (Parkhurst, Law, & Niebur, 2002), our observations of experienced inspectors suggest that color changes in the aircraft surface, in wiring, or within aircraft components are a salient determiner of attentional allocation. The colors of biological contamination, such as mold and algae, can signal underlying corrosion to the experienced inspector (AC 43-204). When the luminance contrast between the defect and its background is very low, color contrast is the only means of discrimination. In such cases, it is critical for the inspectors to have sufficient color vision (personal observation). Subtle color differences are often used for defect detection and identification. Aircraft wiring is color-coded, although often color is a redundant cue in wiring harnesses.

Corrosion is most often detected by visual inspection (AC 43-204; AC 43-4A). It can be described by a variety of colors depending on the composite material on which the corrosion has formed. Detection of uniform etch corrosion is likely a combination of color discrimination, contrast perception, and texture discrimination. Pitting corrosion, on the other hand, is likely a combination of contrast perception (e.g., white or gray powdery deposit) and texture discrimination – not involving the perception of color at all. Often corrosion is rust colored, a cue not as salient to anomalous trichromats or dichromats as to normal trichromats. However, there are many variations of color weakness, therefore, knowledge about the extent of color loss is required to definitively say whether an inspector should be excluded from performing certain types of task, or from being completely excluded from the job. Research is needed to identify the degree and range of color weakness that is acceptable for NDI inspection of aircraft.

The following is a partial list of tasks performed by the NDI inspector (and the typical inspection technique) that may require color discrimination abilities

- discriminating paint colors (visual & borescope)
- lightning strikes (visual)
- corrosion detection (visual)

- discoloration from overheating (visual)
- zonal inspections in cabin (visual - see green)
- cracks (visual & florescent penetrant)
- sulfidation (visual & borescope - dark greenish-gray in hot section of engine, low pressure turbine)

A few studies have been conducted to empirically substantiate the color vision standards within the Air Force (Tredici, Mims, & Culver, 1972) and Coast Guard (Donderi, 1994), while the color vision standard for air traffic controllers has been studied extensively (Mertens, 1990; Mertens & Milburn, 1992; Mertens & Milburn, 1996). However, the majority of vision standards for various occupations have originated from expert opinion or the standards have been borrowed from other occupations. The outcome of this lack of standardization is demonstrated by the fact that police and firefighters have a broad range of color vision standards depending on the state or city in which a department is located. (U.S. Department of the Interior, 2002; Grand Junction, CO; Virginia State Police web site; San Diego Police Department web site).

A vision standard that is based on a single job-related color vision task is that of railroad engineers. Their color vision standard is based on the ability to distinguish between red, green and yellow colored railroad signal lights, this being their primary color vision task (DOT-FRA-SA-98-1; DOT-FRA-49CFR240). Other occupational groups that require the ability to be to distinguish between colors versus having "normal" color vision are the non-deck officers within the Merchant Marines and commercial motor vehicle drivers (Berson, Kuperwaser, Aiello, & Rosenberg, 1998). Although there is no empirically supported color vision standard for the commercial motor vehicle industry, approximately 24% of the states have a color vision requirement for commercial motor vehicle drivers while the remaining states do not. (DOT-FMCSA-synthesis)

The sharing of standards between similar but not identical occupations is common. Space shuttle pilot astronauts who are responsible for shuttle operation, and mission specialist astronauts who have different responsibilities comprised of experimental and payload operations are both required to pass a NASA Class I space physical, which is similar to a pilot's Class I flight physical (NASA HSF web site; NASA Astronaut Selection). In the past, Class I pilots were required to have "normal color vision"; this standard is still in place for all astronauts. However, all classes of pilots (1, 2 & 3) now have an amended color vision standard, which states they must have "the ability to perceive colors necessary for the safe performance of airman duties." (DOT-FAA-14CFR Part 67).

The vision standards set by the FAA should include guidelines for testing of persons in order to detect visual impairments. In a Safety Advisory entitled "Determination of Vision Impairment among Locomotive Engineers" (DOT-FRA-SA-98-1) published by the Federal Railroad Administration (FRA) and the Department of Transportation (Paskiewicz, 2001), a lesson can be learned about the importance of administering appropriate testing procedures. The FRA's expectation was that designated railroad medical examiners would administer color vision examinations. It was not anticipated that it was necessary to specify to the medical examiners the necessary testing procedures and materials. This assumption has been called into question under tragic circumstances when an inappropriate color vision test prevented the detection of a significant color vision deficit, which lead to a major railway accident involving a fatal collision between two New Jersey transit commuter trains (NTSB/RAR-97/01). The NTSB report found that the suspect engineer's medical history showed that he had been administered an acceptable test annually by the same contract physician for 9 years. In the tenth year, the test results showed a deterioration of the engineer's ability to distinguish among some colors. The following year the engineer again demonstrated at inability to distinguish between some colors and was then given a Dvorine Nomenclature Test, a test of color naming ability and not color discrimination, to further evaluate his color vision. The engineer passed the test because many color weak individuals can identify the names of colors by their brightness. The nomenclature test is a precursor to the Dvorine-Second edition test, which is often skipped due to the assumption that most individuals know color names. The examiner failed to administer the accompanying Dvorine-Second edition color vision test, which is the color vision test that actually measures color discrimination abilities. It was ruled likely that the accident was preventable if the physician had used appropriate testing methods to measure the person's ability to distinguish colors (DOT-FRA-SA-98-1). The lesson that should be taken home from this tragic accident is that specific guidelines should be provided along with the limiting visual requirement.

2.2 Visual Acuity

2.2.1 Relevant Terms and Basics

Visual acuity refers to a measure of spatial resolution of a person's vision for a high contrast, static image. Near visual acuity refers to the acuteness or clarity of an image which is approximately 13" away from the person, middle visual acuity is measured when an image is between 13" and 3' from the person being tested, and distance visual acuity is measured at approximately 20'.

When the eye is in focus, a sharp image is formed on the retina; visual acuity impairments result in the loss of sharpness of vision. Visual acuity can be influenced by luminance, contrast, color, surrounding field size and intensity, time available to view an object, glare, refractive error, pupil size, advanced age, attention, IQ, boredom, ability to interpret blurred images, emotional state, corneal opacities, lens or humors, and disease of the retina or optic nerve such as diabetic retinopathy, cataracts, glaucoma or Chorioretinitis (Riggs, 1965; Westheimer, 1987; Sturr *et al.*, 1990; Cornelissen *et al.*, 1995).

There are several types of acuity. The term visual acuity generally means resolution acuity, or the ability to discriminate two small points from a single point. Vernier acuity (Westheimer, 1975), another type of acuity of potential relevance to aircraft inspection, measures the eyes ability to discriminate the offset, or break, between two similarly oriented bars. This type of acuity would be useful for occupational tasks requiring line details, such as reading micrometers or precision gauges requiring the discrimination of a break in contour or alignment.

Distance visual acuity is often recorded as a fraction, with the numerator representing the testing distance, usually 20 feet, or the equivalent, and the denominator representing the smallest line of letters the person being tested can see clearly. If an individual is able to read the 20/20 line of letters from 20 feet away, the letter image is subtending an angle of 5 minutes of arc. A score of 20/40 means that the smallest readable letters were twice this size, so that a 20/20 observer could have read them at 40 feet. These values are usually recorded in feet, 20/20, or outside the United States in meters, 6/6. Near visual acuity can be recorded several ways, commonly it is recorded as a Snellen equivalent, and thus in the fraction form as described above. Near acuity may also be recorded as Jaeger acuity, a non-standardized system based on a printers designation, or it may be recorded in metric notation, M. M units are the distance in meters that the lower case letter subtends 5 minutes of arc.

2.2.2 Visual Acuity: Real-world Performance Literature, Vision Standards, and Relevance to Aircraft Maintenance Inspection

Visual acuity has been the standard for evaluating vision for over 130 years. The acceptance of the Snellen chart in 1862 and the need to create military standards in 1913 provided the basis for the concept that “20/20” acuity is considered to be “good” vision. Visual acuity is often used as an indicator of visual health; however, an individual could see 20/20 on a Snellen acuity chart and still have an undetected ocular disease that has not affected the person’s central vision.

Several research groups have specifically studied the influence of VA impairment on daily living. Szlyk *et al.* (2001) investigated the functioning in daily task performance of individuals with retinitis pigmentosa. The tasks were clustered into three categories: "reading," "mobility," and "peripheral detection." Moderate or worse difficulty in performance was observed only for visual acuity worse than 20/40; log contrast sensitivity less than 1.4 and a visual field smaller than 50-degree in diameter. Haymes (2002) examined the relationship between clinical measures of vision impairment and the ability to perform activities of daily living. Distance visual acuity, near word acuity, contrast sensitivity and visual fields were measured on vision-impaired subjects. Results showed that all vision measures had a high, statistically significant correlation with performance score. Near visual acuity had the strongest correlation followed by contrast sensitivity. Kempen *et al.* (1994) found that visual acuity loss can result in low performance on facial recognition and form discrimination tasks such as reading letters. Thus clinical vision impairment measures can be highly correlated with capacity to perform daily tasks.

West *et al.* (2002) examined the association between performance on selected tasks of everyday life and impairment in visual acuity and contrast sensitivity. The results showed that both visual acuity and contrast sensitivity loss were associated with decrements in function. The relationship of function to the vision measures was mostly linear, therefore, it is difficult to identify cutoff points for predicting disabilities. For heavily visually intensive tasks, like reading, visual acuity worse than 20/30, or contrast sensitivity worse than 1.4 log units was disabling. Both contrast sensitivity and visual acuity loss contribute independently to deficits in performance on everyday tasks. Since cutoff points depend on the task, defining disability using a single threshold for visual acuity or contrast sensitivity loss is arbitrary.

The impact of visual acuity on job performance has been studied extensively. Parssinen *et al.* (1987) examined the need for VA in daily work in different occupational groups. Their results show that there is a need for accurate vision in most occupations and that the visual acuity and refractive error, or need for glasses, of the employees requiring accurate vision should be evaluated prior to beginning work.

It is estimated that 33% of the U.S. workforce have uncorrected, or insufficiently corrected, refractive errors that can affect task efficiency (Ungar, 1971). Workers over the age of 40 with presbyopia, an inability or decreased ability to focus on near images, account for most of this sighted statistic. These individuals require a near vision correction or addition to their present glasses prescription. An individual that has not needed glasses before the age of 40 usually needs glasses to improve their near vision after the age of 40; additionally their near prescription will need to be updated every few years as the near refractive error continues to change over the next several years.

Visual acuity tests are the most prevalent vision test used to screen driver license applicants worldwide. Vision standards for the drivers of personal automobiles, commercial motor vehicle, and school bus drivers vary. Each state has established vision standards, which are imposed in order for an individual to obtain an unrestricted driver's license. These visual acuity requirements range from 20/40 to 20/100 with or without corrective lenses. Visual acuity standards exist in many occupations where safety is imperative. Higgins (1998) evaluated the effect of visual acuity degradation on different components of the driving task. Driving performance was measured while participants wore modified swimmer's goggles to which blurring lenses were affixed in amounts necessary to produce various decreased levels of visual acuity. Acuity degradation was found to have produced significant decrements in road sign recognition and road hazard avoidance as well as significant slower overall driving time. Wood and Troutbeck (1994) compared the driving performance of young, visually "normal" subjects under conditions of simulated visual impairment. Special goggles were designed to replicate the effects of cataracts, binocular visual field restriction, and monocular vision. Simulated cataract resulted in the greatest detriment to driving performance. Studies such as these have potential applications in defining empirically determined vision standards for driver license applicants.

Poor acuity does not always relate to poor performance on visually demanding tasks. A few studies have reported a positive but weak association between visual acuity and automobile crash involvement (Ball & Owsley, 1991; Davison, 1985; Hofstetter, 1976; Liesmaa, 1997; Marottoli, *et al.*, 1998), while other research has largely failed to provide convincing empirical evidence for decreased vision's role in traffic accidents (Burg, 1967, 1968; Decina & Staplin 1993; Ivers and Mitchell, 1999). Having "good" visual acuity is not closely correlated to visual tasks such as seeing objects of different sizes and contrasts, whether visibility is clear or poor. Studies with pilots in simulators and in field trials have shown that acuity alone is not an absolute indicator of actual task performance (Ginsburg *et al.*, 1982; Ginsburg, *et al.*, 1983). Regardless of these findings, visual acuity is still used as an indicator as to whether or not a person can see well enough to drive or pilot vehicles safely.

One study investigated the uncorrected distance visual acuity necessary for firefighters to perform “acceptably” (Padgett, 1989), and several studies have provided empirically valid uncorrected visual acuity standards recommendations for police officers. In these particular studies the vision standard was based on the specific visual needs of each specific occupation (Sheedy, 1980; Good & Augsburger, 1987; Good & Maisel, 1998). Although these recommendations exist, there is significant variability in the required vision standards between different police agencies throughout the United States (Holden, 1984). Other occupations have variable standards as well depending on the city or state in which an individual works, lifeguards and firefighters are examples. (New York State Parks web site; Broward County, FL web page; Washington State Department of Personnel web site; U.S. Department of the Interior, 2002; Grand Junction, CO web site). The minimal uncorrected visual acuity requirement for military aircrew and air control personnel has been evaluated experimentally (Draeger & Schwartz, 1989). However, most aviation governing bodies, such as the FAA, no longer require a specific uncorrected visual acuity. At this time the FAA’s best-corrected vision standards for all classes of pilots are similar to the international ICAO vision standards. As with standards that have not been empirically derived, these standards appear to be based on expert opinion rather than job task analysis and empirical testing. Occasionally smaller individual industries, such as a basket manufacturing company, have taken the initiative and made arrangements for their own job-related vision standards to be empirically developed for their work force. (Ross, 1978)

Good *et al.* (1996) performed a systematic study on setting job-related vision standards. The study, as the authors claimed, can serve as a model for the application of visual standards to the workplace. In this study, the critical factors for performing specific visual tasks for 40 job classifications at a manufacturer of hand-woven baskets and accessories were identified. For each class of job, the study was carried out in four steps: 1) identifying the primary duty; 2) identifying specific visual tasks; 3) identifying specific visual requirements for VA, binocularity, color vision and visual field; and 4) assessing the level of visual performance necessary to accomplish the tasks and setting up the visual standards. Each class of job required sharp vision at near working distances. For example, quality inspection tasks included identifying chips, small cracks and other subtle inconsistencies in wooden splints. The research determined the level of near visual acuity necessary for each inspection task. In the experiments observers with “normal” vision performed inspection tasks under three viewing conditions: 1) normal viewing: 2) a small amount of cylindrical blurring to decrease VA moderately and 3) a large amount of cylindrical blurring to decrease VA greatly. The altered near acuity was compared against each of the worker’s performance errors. The results indicated that the critical point of blur was 20/30. Above this acuity level the number of errors increased in a linear fashion. Therefore, the conclusion was that 20/30 near VA should be the standard for individuals’ inspection tasks at this facility. Since more than 98% of the US population has at least 20/25 corrected VA, the 20/30 VA standard will not eliminate a significant number of workers from these jobs.

Industries without their own specific visual acuity standards borrow from other industry standards, an example would be the British electronics industry that uses the vision standards set forth by the American Society of Mechanical Engineers' Code for Boiler and Pressure Vessels (Kennedy, 1989). The ASME's vision standards are for Nondestructive Examination , NDE, personnel involved in the inspection of nuclear power plant components (American Society for Mechanical Engineers, 2001). As stated earlier, some police departments have taken the initiative to empirically validate their visual acuity standards; however, there are other police and correctional departments that have instead applied the vision standards established by the National Fire Protection Association for firefighters, despite the dissimilarity of the various job tasks between the different occupations (MED-TOX Health Services).

There are many standards without clear empirical backing, including those for drivers of commercial motor vehicles (Federal Motor Carrier Safety Administration-49 CFR Part 391.41), Merchant Marines (U.S. Coast Guard Marine Safety Manual III), welding inspectors (American Welding Society, 2002), and locomotive engineers (DOT-FRA 49CFR240). It is unclear as to the origin for the visual acuity standards for the Air Force and the Coast Guard, but interestingly their distance and near visual acuity standards are exactly the same, one likely having barrowed from the other (USAF AFI 48-123, U.S. Coast Guard-DOT, 1988).

Finally, there are the industries that are interested in setting their own vision standards but have not been able to empirically investigate the specific vision needs for their line of work. Interestingly, they recognize that borrowed standards from other fields are not of use to them. An example industry is that of bridge inspectors (Glenn Washer, Director of NDE Center in McClain, VA., personal communication; DOT-FHA, 2001).

When setting standards, including visual standards, the purpose of the qualifying test must be defined, the medical personnel performing the evaluation should have detailed testing protocol available, and the pass/fail criteria should be unambiguous.

Grundy (1997) proposed a general task analysis method for specifying visual acuity standards. The methods included: 1) determining the working distances involved and the size of visual details; 2) using a nomogram to determine the minimal visual acuity for the task and 3) setting a visual acuity standard at approximately twice the minimum level. However, in many tasks the viewing distances and the flaw sizes were difficult to determine, such as the tasks involved in aircraft inspection. Thus elaborated visual experiments are needed.

The detectability and discriminability of many airframe and engine defects may depend on the resolution of the human eye. Examples of tasks that are performed by the NDI inspector (and the typical inspection technique) that may require spatially acute visual abilities include:

- discriminate wear marks on a machine part (visual & borescope)

- small crack discrimination from other anomalies (visual, borescope, florescent penetrant)
- wiring frays (visual)
- reading computer screen (eddy current & ultrasonic)
- pitting, scoring, porosity, and tool marks (visual & borescope)
- fit of seals, bonds, gaskets, and sub-assemblies in difficult to reach areas (visual & borescope)
- assess Foreign Object Damage (FOD) in aircraft, airframe, and power plants (visual & borescope)
- paint chips (visual)
- cracks, nicks, missing material (visual)

Essentially all the aircraft inspection work described above requires an inspector to search for fine flaws in materials. Thus sharp visual acuity at near distances may be needed.

But what of inspectors whose vision is not completely correctable? Can they still perform the tasks at hand? It is likely that visual crack detection would be rendered more difficult, but if contrast perception (see section below on this topic) is intact, then the inspector may not require 20/20 or even 20/50 vision.

2.3 Visual Field loss

2.3.1 Relevant Terms and Basics

The normal visual field for binocular vision extends to approximately 190 degree horizontally and 120 degree vertically (Weston 1962). The 0-4 degree central-most region is called the fovea, where the sensitivity to a stimulus is the highest. The rest of the much larger field is called the periphery. Sometimes, especially in medical clinics, the visual field of roughly 5 to 10 degree is called the parafoveal field. While humans rely on foveal vision for reading, discriminating, and object recognition (Latham and Whitaker, 1996) peripheral vision is essential for sensing movement, searching targets, and orientation. Color discrimination, contrast sensitivity, and acuity are markedly worse with increasing eccentricity (Martin *et al.*, 2001; Rovamo, 1983). Contrast sensitivity declines can be attributed to a reduced cortical representation with eccentricity (Rovamo, 1983), while color vision deterioration has been attributed to reduced color specificity in peripheral retinal cells (Martin *et al.*, 2001).

The type of visual field deficit depends on the lesion size and location. Individuals with peripheral vision loss can retain clear central vision. Deficits may include homonymous hemianopias, quadrantopias, scotoma (area of decreased sensitivity) and visual constrictions. In some cases small patches of retinal activity on the periphery are preserved, making it possible to detect movement and objects that assist with one's orientation. The most common causes of visual field loss are glaucoma, retinal disorders, and cataract.

Age influences the extent of the useful visual field dramatically. The incidence of visual field loss is 3.0% to 3.5% for persons aged 16 to 60 years but is approximately 13.0% for those older than 65 years (Johnson and Keltner 1983). The lateral visual field begins to decline at the average age of 35 years (Burg 1968; Ball, Beard, Roenker, Miller, Griggs, 1988).

2.3.2 Visual Fields: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

Alfano and Michel (1990) examined the role of peripheral vision in visuomotor activities such as walking, reaching, and forming a cognitive map of a complex field. They used goggles that limited the scope of the normal field of view to 9 degrees, 14 degrees, 22 degrees, or 60 degrees. Each restriction of peripheral field information resulted in some perceptual and performance decrements, with the 9 and 14 degree restrictions producing the most disturbance, especially in forming a cognitive map which is important for visual search.

Visual search in industrial inspection has been widely studied since the 1960's Badalamente & Ayoub 1969). As summarized by Schoonard and Gould (1973), inspectors must simultaneously and rapidly look for multiple defect types. As a result, they can miss up to a quarter of the defects.

Efficient visual search is characterized as systematically scanning a field of fixed size. Hockberg (1978) and other researchers have suggested that peripheral vision guides the scanning field to the potential target site where the features can then be scrutinized. However, it had been difficult to find the optimal field size and to study the relationship between search performance and visual field, because it is hard to isolate the effects of central and peripheral vision. Kundel *et al.* (1991) studied this issue by using a system called the eye-position interactive display. Subjects searched for lung nodules within human chest images. The eye-position interactive display positions the nodule within a specific part of the visual field without disturbing the chest image appearance. Using this system Kundel et al. studied the optimal scanning field size and the effectiveness of peripheral vision in guidance of foveal vision to the nodules. They found that the time required to scan the image and fixate the nodule was shortest for nodules that were both reported and accessible to peripheral vision. A stepwise concentric reduction in the peripheral field size only affected search performance when the field was less than 5 degrees. (The chest images subtended about 25 degrees.) These data support the hypothesis that the optimal scanning strategy for lung nodules consists of spacing fixation clusters 5 degrees apart, and that the peripheral field beyond 5 degrees adds little to the discovery of nodules in a systematic search process. Peripheral vision guides the gaze to inconspicuous nodules and accelerates the discovery of some nodules.

A great deal of research has been done on vehicular driving performance with normal and abnormal visual fields. Johnson and Keltner (1983) performed visual field screening of 10,000 volunteer driving license applicants. They found that drivers with binocular visual field loss had accident and conviction rates twice as high as those with normal visual fields. Wood and Troutbeck (1994) simulated restricted vision using goggles designed to replicate the effects of cataracts, binocular visual field restriction, and monocular vision. Simulated cataract resulted in the greatest detriment to driving performance in a simulator, followed by binocular visual field restriction. Schiefer *et al.* (2000) studied the influence of some typical visual field defects, such as scotoma, on visual perception. The results demonstrated that evaluation of visual field borders alone is not sufficient for evaluating driving fitness.

Recent studies support the idea that current clinical screening tests of visual fields (perimetric testes) are not good predictors of performance (Myers *et al.*, 2000). Schulte *et al.* (1999) found no differences in driving performance (driving speed, reaction time, and driving error rate) between subjects with normal and defective visual fields, as measured with classic perimetric tests. In many occupational studies, researchers often prefer the measurement of the "useful field of view" (UFOV) to the conventional measurement of the sensory visual field. The UFOV task, developed by Ball and colleagues (Sekuler and Ball 1986; Ball, Beard, Roenker, Miller, and Griggs, 1988; Ball, Owsley & Beard, 1990) relies on higher-order skills, such as selective and divided attention and rapid visual processing speed. Several studies have shown that drivers with the most severe restrictions in their UFOV tend to have the highest number of crash involvements (Ball & Owsley, 1991; Owsley *et al.*, 1998a,b; Owsley and McGwin, 1999; Myers *et al.*, 2000) and that the addition of screening tests beyond UFOV alone do not increase predictive validity (Myers *et al.*, 2000).

There is a lack of sited empirical research to support most occupational visual field requirements. Air traffic controllers in terminal and center positions must have both "normal" central and peripheral visual fields. They are required to have 140 degree fields in the horizontal meridian and 100 degree fields in the vertical meridian (U.S. Office of Personnel Management, 2001). The coast guard's standards leave nothing to interpretation, their standards are specific in eight separate meridians, i.e. superior, superior nasal, nasal and so forth. The temporal meridian, measured from straight ahead outward toward the ear, for each eye is 85 degrees; therefore, together the binocular horizontal visual field requirement is 170 degrees for coast guard applicants (U.S. Coast Guard). Other occupations with specified size requirements in degrees of field include merchant marines, wildland firefighters and railroad engineers (U.S. Coast Guard).

Visual field standards are sometimes borrowed from one occupation to the next. The visual field standard for forklift operators at one company came from the Federal Department of Transportation's standard for commercial drivers (Ross, 1978).

Not all occupational visual field standards are specified as a numeric value although the qualifying designation of “normal” includes no explanation as to what size or shape constitutes a “normal” field. Examples of Federal occupations with the general requirement of "normal" visual fields includes border patrol agents, customs patrol agents, mining safety inspectors, nuclear materials couriers, and criminal investigators. Our literature search uncovered no visual field requirements for Federal U.S. Marshals, correctional officers, security guards, or food inspectors.

Commercial motor vehicle drivers are required to have 70 degree visual fields in the horizontal meridian for both the right and left eyes, this equals a 140 degree binocular field (Federal Motor Carrier Safety Administration 49 CFR Part 391.41; Berson *et al.*, 1998; Ross, 1978). The majority of states in the U.S. do not have a visual field requirement for private motor vehicle drivers and of the approximately 15 states that do, the horizontal visual field requirement ranges from 100 to 140 degrees (North, 1985).

Empirical research has been conducted to determine visual field requirements for correctional officers. The standard includes the need for two functioning eyes and an associated full visual field of no less than 120 degrees in order to prevent a decrease in acceptable job performance when supervising inmates while in the same room or area (MED-TOX web site).

Disease or age-related visual field restrictions are not the only parameters that can limit the aircraft maintenance inspectors' peripheral vision. Pyramid-type task analysis has revealed that the borescopes can limit the inspector's field of view, removing beneficial landmarks (Drury, 2001). In addition, the visual field can be restricted by spectacle frames and opaque side shields on safety spectacles.

Melloy *et al.* (2000) developed a model that characterized the trade-off between the search speed and accuracy in aircraft inspection. The accuracy depends on the number of fixations, the probability of detection, and the search field size. With a restricted field of view, the number of fixation would increase accordingly in order to cover the same size of the search field. This in turn would decrease the accuracy of visual inspection.

Many studies on visual search in inspection have been devoted to improving search strategies (Wang *et al.*, 1997; Drury 1990; Megaw and Richardson 1979; Tsao *et al.*, 1979; Gramopadhye *et al* ., 2000). These studies show that the most useful search strategies include systematic search and expanding the UFOV. Few studies have tried to quantify the optimal visual field required for those search strategies. Moreover, it is unclear how weak vision in a local scotoma of the visual field would effect inspection.

In reviewing the above occupational visual field requirements, no specifics are described as to the type of testing to be given when assessing visual fields. An easily administered and acceptable method of assessing fields is confrontations, this requires an individual to indicate when s/he sees or no longer sees a target stimuli in their peripheral vision. In general this type of testing will not reveal mild to moderate defects or field loss in the non-peripheral, or more central, portion of the field.

So, does an aircraft maintenance inspector need parafoveal or peripheral vision to adequately perform his duties? The UFOV methodology may serve as a tool to answer this question. Inspectors look for many things at once, search for the target and then discriminate the target from other parts of a visual scene. Tasks such as these, requiring divided attention, relate much more highly to UFOV measures than does classical clinical perimetry (Ball, Owsley & Beard, 1990).

Again the question arises as to whether any of these standards can be used for maintenance inspectors and once again the answer is no. Only a handful of standards are supported by empirical data and the tasks performed within these occupations are too dissimilar to those of maintenance inspectors to generalize the results.

2.4 Contrast Perception

2.4.1 Relevant Terms and Basics

Practically speaking contrast sensitivity is a measure of the limit of visibility for low contrast patterns -- how faded or washed out can images be before they become indistinguishable from a uniform field? (Think of driving in a fog). Only if there is sufficient contrast do objects become so distinct from the background as to be detectable. Contrast sensitivity is typically plotted as a function of the size (coarse/fineness) of image features, or the spatial frequency. This plot is called the contrast sensitivity function (CSF). The test image shown below was first produced by Campbell and Robson (1968) to illustrate the form of the function in a very intuitive manner -- using everyone's own visual system and without time-consuming measurements.

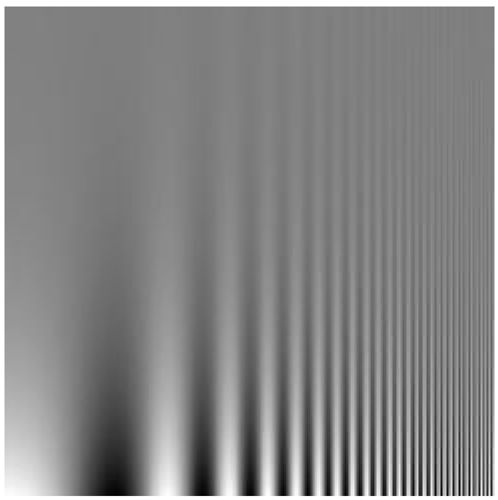

Figure 3. Contrast sensitivity demonstration.

2.4.2 Contrast Sensitivity: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

The CSF has emerged after over 30 years of scientific testing as a more comprehensive way than Snellen acuity to describe vision (Proenza *et al.*, 1981; Committee on Vision, National Research Council, 1985). Recall that in Section 2.3 we described visual acuity as a measure of the smallest detail that the visual system can resolve. When assessing visual acuity, one is interested only in the spatial (size) factors that limit vision, so other factors (such as contrast) are optimized. Since visual objects come in a variety of sizes, shapes, and contrasts, the visual system's sensitivity should be tested with a set of simple targets that can represent any size, shape, or contrast. When an eye chart is printed with light gray ink on a gray card stock, rather than with very black ink on white card stock, the letters are harder to see (Regan, 1988). The letters' reduced contrast limits visual acuity suggesting that performance cannot be assessed based on size alone. Measures of the CSF inform as to how both contrast and size limit vision. Established techniques for measuring threshold levels of contrast in a quick, simple, and inexpensive manner with a vision test chart have been proven for almost 20 years in clinical and performance trials (Ginsburg, 1984; Evans & Ginsburg, 1985).

Two people with exactly the same visual acuity can have significantly different contrast sensitivity functions. Many instances in which contrast sensitivity loss was detected when visual acuity was normal have been reported. Although impairments in visual acuity are reflected in measures of contrast sensitivity (Marmor & Gawande, 1988), experiments have shown that visual acuity and contrast sensitivity measurements can not predict each other on one measurement alone (Peregrin *et al.*, 1992). Therefore, it is necessary to include both visual acuity and contrast sensitivity requirements within any vision standard.

Contrast sensitivity testing provides early detection of serious eye diseases and/or conditions that a standard letter acuity chart may not detect until the condition is more advanced. Such diseases and/or conditions include cataracts, glaucoma, amblyopia, macular degeneration, keratoconus, and optic neuritis. Contrast sensitivity testing has also been shown to detect other types of diseases and/or conditions including diabetes, cerebral lesions, AIDS and Alzheimer's disease at early stages, sometimes before other symptoms may appear. CSF measurements are highly correlated with the patient's perceived visual disability, particularly their subjective assessment of the effect of vision on their mobility-orientation (Elliott, Hurst, & Weatherill, 1990).

Population data has been obtained for visual acuity and contrast sensitivity (Grimson, Schallhorn, & Kaupp, 2002; Haymes, Johnston , & Heyes, 2002; Mantyjarvi & Laitinen, 2001; West, Rubin, Broman, Munoz, Bandeen-Roche, & Turano, 2002) and related to real world performance. Quite a few studies have been done on large populations of automobile drivers. A strong relationship between high spatial frequency contrast sensitivity loss and visual acuity with self-reports on driving difficulty was shown in 288 drivers over the age of 55 with cataract compared to a control group of 96 drivers with no indication of cataract (McGwin, Chapman, & Owsley, 2000). A study done in the UK showed that automobile crash involvement obtained from the driving records of 690 drivers increased for those drivers with below average low contrast visual acuity (Slade, Dunne, & Miles, 2002). In Canada, it is acknowledged that reduced contrast sensitivity can affect driving ability in spite of having adequate visual acuity. They also acknowledge that research is needed to understand what level of reduced contrast sensitivity represents an unacceptable driving risk (www.eyesite.ca).

Significant acuity and CS loss does not affect mobility in the environment, but it does affect more vision intensive tasks such as the ability to read - visual acuity worse than 0.2 logMAR (20/30) or contrast sensitivity worse than 1.4 log units was disabling (West *et al.*, 2002). Poorer scores for acuity, contrast sensitivity, and UFOV were independently associated with longer times to complete everyday tasks such as reading ingredients on cans of food, reading instructions on medicine bottles, finding a phone number in a directory, or locating items on a crowded shelf and in a drawer (Owsley, McGwin, Sloane, Stalvey, & Wells, 2001).

So how does contrast sensitivity relate to NDI/NDT task performance? Following is a list of potential airframe or powerplant defects detectable using contrast perception.

- cracks
- corrosion (visual & borescope)
- weld joints
- solder connections
- adhesive disbonds
- identifying water or skin bulges (X-ray)
- reading computer screen (eddy current & ultrasonic)
- pitting, scoring, porosity, and tool marks (visual & borescope)
- fit of seals, bonds, gaskets, and sub-assemblies in difficult to reach areas (visual & borescope)
- assess Foreign Object Damage (FOD) (visual & borescope)
- rippling on airframe indicating subcutaneous corrosion
- seams, voids, pits
- other surface, or subsurface, discontinuities in ferro-magnetic materials

Based on our observations of crack and corrosion detection thus far, contrast perception may be a most critical visual process in NDI inspection. Aluminum and magnesium corrosion appears as a white or gray powder that shows under or against the painted surfaces. To detect this powder likely requires contrast perception. Further research is needed to confirm this contention.

A common way for inspectors to increase surface crack detectability is to shine their flashlight at a 5-45 degree angle relative to the surface (AC 43-204). In visual psychophysical terminology, they have increased the object detectability using "shape from shading" cues (Cavanagh & Leclerc, 1989). These shadows can accentuate the depth and form of objects. Clearly defined shadows can improve visibility.

In the past, a few military standards documents such as MIL-STD-271 have addressed contrast sensitivity requirements. This document advised that radiographic personnel be tested for brightness discrimination, but no guidelines were given as to the desired standard or testing procedure (Klevin & Hyvarined, 1999). The most up to date document that supersedes MIL-STD-271, NAVSEA T99074-AS-GIB-010/271, does not mention a brightness discrimination or contrast sensitivity standard.

We were unable to locate current contrast sensitivity standards in industry or the military; however, contrast sensitivity is being considered as a future tool for evaluating visual requirements, especially in those individuals with borderline visual acuity (Gray, 1985). Presently data is being gathered from within the military aviation community in order to establish normative contrast sensitivity values. In the future these data could possibly be used to set up contrast sensitivity standards for commercial and general aviation pilots.

2.5 Perception of Depth

2.5.1 Relevant Terms and Basics

In binocular vision (two eyes), the impression of spatial depth is enhanced as compared to monocular (one eye) vision. Because the eyes are located at different positions in the head, there are slight geometric differences in the world representation visualized in the two retinas. These differences between the images formed by a single fixated object on the right and left eye retinas are greater, the closer the object. The disparity between the two images is a prerequisite for depth (three dimensional) perception. Based on this, the implication for aircraft maintenance inspection MAY be that inspectors should have normal binocular vision. However, with just one eye, one can use size differences, amount of overlap, and parallactic shifts during head movements to achieve a certain degree of depth perception (albeit the result is less informative than that derived from full binocular vision). Therefore, it is unknown if monocular vision is adequate to perform inspection tasks.

2.5.2 Perception of Depth: Real-world Performance Literature and Relevance to Aircraft Maintenance Inspection

Assume that an inspector has binocular vision, but has disrupted binocular fusion. This can be simulated in yourself by pressing one eyelid lightly with a finger while looking at an object. The object is now imaged “incorrectly” on the displaced retina and you “see double” because binocular fusion is disrupted. If an aircraft maintenance inspector has two eyes that do not work, or move, together, (this often happens during times of fatigue or when a person has a visual condition called strabismus), then his perception of the aircraft component may be distorted. In addition, the use of visual aids, such as some forms of boroscope, result in different images being perceived in the two eyes. There are cortical mechanisms that prevent seeing double. One of these is the low visual acuity in the peripheral retina. A second is a binocular inhibitory mechanism in the central nervous system that suppresses perception in one or the other of two disparate images. Because of this inhibitory mechanism there is a binocular rivalry, an alternating perception of the image in one eye and then the other. In addition, parts of each eyes’ image may be visible simultaneously, but only next to one another, and not superimposed. In this binocular rivalry, contours are more effective than uniformly shaded surfaces. This inhibitory mechanism differs between individuals.

Using stereo photographs of real objects, Doorschot, Kappers, & Koenderink (2001) varied the position of a light source to obtain different shape from shading cues. They found that surface attitude settings were based on both these shading cues as well as binocular disparity cues.

Few occupations have binocular vision requirements and even fewer have conducted any type of research to verify their specific binocular vision standards. One paper was found describing a private company that contracted to have appropriate vision standards devised for its various job positions. An initial recommendation was made that their forklift operators have 80" of stereoacuity. This was based on observations made of workers during normal forklift operations and, while one of their eyes was occluded during forklift operations. Upon screening the vision of these same forklift operators it was found that 20% did not meet the standard. However, their safety record was devoid of accidents causing injury or product damage. This non-empirically determined standard was removed due to the safety record and the workers ability to perform acceptably even without "good" stereoacuity. (Good, Weaver, & Augsburger, 1996).

A few binocular vision standards are stated in terms of the eyes' muscular balance and the eyes' ability to work together, verses a specific numeric binocular acuity value as described before. For instance the Department of the Navy does not have a depth perception requirement for aircrew maintenance personnel, but they do require that individuals have no "obvious hetertropia (eye turn) or symptomatic heterphoria (poor bi-ocular alignment)" (Department of the Navy, Bureau of Medicine and Surgery, 1996). Years ago Air Traffic Controllers had a steroacuity standard that is no longer in place. Presently the requirement for phorias for Air Traffic Controllers in terminal and center positions states that if they have a horizontal phoria that measures greater than 10 prism diopters in either horizontal direction or a vertical phoria that is greater than 1 1/2 prism diopters they must be evaluated by an eye specialist to establish that they meet the broader requirements of bifoveal fixation and that the two eyes work together (U.S. Office of Personnel Management, 2001). The standards for a first-class airman's medical certificate are similar in that they require bifoveal fixation which must be determined if an individual is found to have more that 1 prism diopter of hyperphoria or 6 prism diopters of esophoria or exophoria, the horizontal phorias (FAR, Part 67.103). The standards for the U. S. Coast Guard simply state that there shall be "no strabismus (eye turn) or diplopia (double vision)" (U.S. Coast Guard).

As with visual field standards, many occupations state that binocular vision needs to be "normal" without giving guidelines as to what kind of ocular alignment or stereoacuity constitutes "normal". Examples of occupations having visual acuity standards in addition to this loose binocular vision standard within the Federal Government include U.S. Marshals, nuclear materials couriers, wildland firefighters, criminal investigators, and mine safety personnel (U.S. Coast Guard). Examples of those without any standard include border and customs patrol officers, corrections officers, security guards, pharmacists and dental officers (U.S. Office of Personnel Management, 2001). Then there is the occupation of food inspector with a slightly more vague binocular vision requirement of "clear and accurate depth perception".

It is not only unclear as to how the above-mentioned standards were chosen, but there are no outlined specifications as to which binocular vision testing procedures are clinically acceptable when testing for these standards. Once again, due to this and the fact that none of the occupations that were found to have binocular vision standards are similar to those of aviation maintenance inspectors, these standards should not be adopted as standards to qualify an aviation maintenance inspector's vision.

3.0 Discussion

Although non-destructive testing does not ensure that aircraft components will not fail, it does provide a significant safeguard against such failures. The sense of sight provides a valuable non-destructive testing approach. It is therefore imperative that aircraft maintenance inspectors possess good vision. It is difficult, if not impossible, to eliminate human error in the process of inspection. Therefore interventions must be developed to reduce these errors and make the process more error-tolerant. One error mitigation strategy being pursued by the FAA is to standardize the vision requirements for the maintenance inspection industry.

Vision standards have been written for other occupations including correctional officers, firefighters, pilots, welders, automobile drivers, and astronauts. Typically, optometrists or ophthalmologists provide their expert opinions about what the requirements should be for a particular occupation. Sometimes the standards of unrelated occupations are borrowed. Seldom have occupational vision standards been empirically derived. This is surprising since different jobs make different visual demands upon the worker and require different visual skills. Standards for specific job classifications should be based on the vision requirements of the tasks performed on that job.

Recruitment, testing, selection, and training costs are high. The rejection of qualified persons imposes an unnecessary cost on maintenance facilities. While the failure of proper performance on visual tasks could be catastrophic, persons with refractive errors such as correctable myopia who can perform the job should be permitted to do so. Vision requirements should be based on a demonstration that, for example, 20/25 near or 20/50 distance visual acuity is actually needed to perform the essential task. If the task is not generally performed alone (i.e., there are several people in close proximity who provide assistance) then these tasks should not be imposed with a vision requirement for all the individuals. In addition, vision requirements must be based on tasks that cannot be modified by current available technology to assist the worker's vision. About 8-10% of the U.S. male population has some form of color vision deficiency. About half of these have color defects that are so mild as to have no practical impact on the performance of basic color naming tasks. In applied settings, color-coded wiring may be identifiable through patterns or a warning light might appear dark rather than red, thus being detectable by an individual with a specific deficit.

Because the maintenance work performed by a licensed aircraft mechanic or inspector changes rapidly due to advances in computer technology, solid-state electronics, and fiber composite structural material, there is an associated need to develop a methodology that will permit fast, representative determinations of visual requirements. Here we propose such a task-based methodology. There are many variations of vision loss, therefore, knowledge about the extent of the loss is required to definitively say whether an inspector should be excluded from performing certain types of task, or from being completely excluded from the job. Research is needed to identify the degree and range of vision weakness that is acceptable for NDI inspection of aircraft.

Four years ago a major study was conducted by the Federal Highway Administration to see if the visual inspection of bridges was accurate and reliable (Glenn Washer, Director of NDE Center in McClain, VA., personal communication; DOT-FHA, 2001). The study involved the collection of performance data including results from inspections, inspector' characteristics, and the inspection environment. Based on the results of this study, it was recommended that research be performed to determine if vision standards would have a significant impact on the inspection process.

Similarly, it is not known if standardizing the vision requirements for maintenance inspection will have a significant impact on performance. NASA Ames Research Center has proposed a methodology which will permit such a determination (Beard *et al.*, 2002). Through systematic simulation of typical visual defects, such as blurred vision, color vision loss, contrast sensitivity loss, and visual field defects, the effects of such defects can be assessed. In addition, these data can be used to define the range of defect that can still exist without effecting performance.

We propose the need to assess performance as a function of anomalies in the contrast sensitivity function. Contrast sensitivity is not traditionally included in occupational vision standards. On the other hand, visual acuity standards are always included in the standards. Although high contrast acuity is undoubtedly important for some everyday tasks, natural scenes are predominantly composed of low contrast information (Brady & Field, 2000). Contrast sensitivity has been found to be a better predictor of target detection and recognition than standard visual acuity measures for pilot's attempting to detect ground-to-air targets in field studies (Ginsburg *et al.*, 1983) and in simulators (Ginsburg *et al.*, 1982), for detection and discrimination of faces (Beard & Ginsburg, 1991), for military tank detection in outdoor scenes (Rohaly *et al.*, 1997) or simulated aircraft on a runway (Ahumada & Beard, 1997). Thus, measuring the ability to see low contrast images may be worth considering when determining vision standards and tests for individuals needing to see small objects at low contrast levels (301).

Is there sufficient information in the published literature to write a vision standard for aircraft maintenance inspection? Currently, each facility determines the vision standards for their aviation maintenance inspectors. In trying to make these standards more universal throughout the aviation maintenance community the need arises to determine if an empirical evaluation of the necessary visual requirements has been carried out for a similar occupation so that all or part of those standards can be used in the aviation maintenance industry. Based upon our literature review, of the occupations that have empirical justification for their standards, none of the job requirements are similar enough to those of an aviation maintenance inspector to substantiate a borrowing of standards. Pilots, air traffic controllers, mariners, police and firefighters all have various job specific tasks, most of which do not overlap with those of an aviation maintenance inspector. It would be unacceptable to borrow vision standards from any of these occupations due to the extreme differences between each of their visual tasks to the tasks of aviation maintenance inspectors. Of the occupations that may have some similar job tasks, none have empirically backed vision standards.

In conclusion, our review of text and WEB-based search for occupational vision requirements, knowledge gained from site visits to major aircraft maintenance facilities, relevant information from technical, mechanical, and inspection textbooks, the FAA maintenance human factors web-site, and the human vision literature revealed no studies which allow generalization of findings – the occupational tasks are too dissimilar. The standards for aircraft maintenance inspectors should reflect a more sensitive, evidence-based approach than to just use the existing literature based on other occupational needs. Any vision standard to be developed for aviation maintenance inspectors must take into account their specialized inspection tasks and the environments in which they work.

4.0 References

Adams, A. J. & Tague, M. K. (1985). Performance of air traffic control tasks by protanopic color defectives. American Journal of Physiological Optics, 62, 744-750.

Alfano, P. L., Michel, & G. F. (1990). Restricting the field of view: perceptual and performance effects. *Perceptual and Motor Skills*, 70(1), 35-45.

The American Society of Mechanical Engineers. (2001). *Boiler and Pressure Vessel Code* (section 9), Publication IMA-2321.

The American Welding Society. (2002). Eye examination. In *AWS D1.1/D1.1M:2002, Structural Welding Code – Steel* (section 6.1.4.4, p. 200).

Amos, J. F. (1998) *Diagnosis and management in vision care* (pp. 686-688). Stoneham, MA: Butterworth.

Anderson, R. S. (1996). The selective effect of optical defocus on detection and resolution acuity in peripheral vision. *Current Eye Research*, 15(3), 351-3.

Anderson, S. J., & Yamagishi, N. (2000). Spatial localization of colour and luminance stimuli in human peripheral vision. *Vision Research*, 40(7), 759-71.

Awareness grows of importance of human factors issues in aircraft maintenance and inspection. (1996). *ICAO Journal*, 51(1), 19-21.

Badalamente, R. V. & Ayoub, M. M. (1969). A behavioral analysis of an assembly line inspection task. Human Factors, 11. 339-352.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: expanding the useful field of view. *Journal of the Optical Society of America A*, 5(12), 2210-9.

Ball, K. K. & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*, 33, 583-595.

Ball, K. K., Owsley, C. & Beard, B. L. (1990). Clinical visual perimetry underestimates peripheral field problems in older adults. *Clinical Vision Science*, 5, 113-125.

Behrmann, M., Watt, S., Black, S. E., & Barton, J. J. (1997). Impaired visual search in patients with unilateral neglect: An oculographic analysis. *Neuropsychologia*, 35(11), 1445-58.

Berninger, T., Drobner, B., Hogg, C., Rudolph, G., Arden, G. B., & Kampik, A. (1999). [Color vision in relation to age: a study of normal values.] *Klin. Monatsbl. Augenheilkd.*, 215(1), 37-42. [Article in German.]

Berson, F. B., Kuperwaser, M. C., Aiello, L. P., & Rosenberg, J. W. (1998). Visual requirements and commercial drivers. Retrieved March 21, 2002, from Department of Transportation Web site: http://www.fmcsa.dot.gov/Pdfs/VisionFinalReport10-16-98.pdf

Best, P. S., Littleton, M. H., Gramopadhye, A. K., & Tyrrell, R. A. (1996). Relations between individual differences in oculomotor resting states and visual inspection performance. *Ergonomics*, 39(1), 35-40.

Brady, N. & Field, D. J. (2000). Local contrast in natural images: Normalisation and coding efficiency. *Perception*, 29, 1041-55.

The British Institute of Non-Destructive Testing. (2002). General requirements for qualification and PCN certification of NDT personnel, vision requirements. PCN document PSL/44. Retrieved April 14, 2002, from http://www.bindt.org/Mk1Site/PCN.pdfs/GENissue3.pdf

Broward County, Fort Lauderdale, FL. (n.d.). Employment opportunity, senior lifeguard. Retrieved July 15, 2002 from http://205.166.161.20/hrcurrjobs/XML/690.htm.

Burg, A. (1967). Some preliminary findings concerning the relation between vision and driving performance. *Journal of the American Optometric Association*, 38, 372-377.

Burg, A. (1968). Lateral visual field as related to age and sex. *Journal of Applied Psychology*, 52, 10-15.

Campbell, F. W. & Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology*, 197, 551-566.

Canadian Ophthalmological Society. (2000, November 24). Clarification on vision standards and driving. News release. Retrieved September 27, 2002 from http://www.eyesite.ca/english/drivingstdnov24.html

Cavanagh, P., & Leclerc, Y. G. (1990). Shape from shadows. *Journal of Experimental Psychology: Human Perception and Performance*, 16, p. 910.

Chaparro, A., Stromeyer, C. F. 3rd, Huang, E. P., Kronauer, R. E. & Eskew, R. T. Jr. (1993). Colour is what the eye sees best. *Nature*, 361, 348-50.

Cline, D., Hofstetter, H., & Griffin, J. (Eds.). (1989). *Dictionary of Visual Science*. Chilton/Haynes.

Cooper, B. A., Gowland, C., & McIntosh, J. (1986). The use of color in the environment of the elderly to enhance function. *Clinical Geriatric Medicine*, 2(1), 151-63.

Cornelissen, F. W., Bootsma, A. & Kooijman, A. C. (1995). Object perception by visually impaired people at different light levels. *Vision Research*, 35, 161-168.

#CSWIP

Deco, G. & Zihl, J. (2001). A neurodynamical model of visual attention: Feedback enhancement of spatial resolution in a hierarchical system. *Journal of Computational Neuroscience*, 10, 231-253.

Dick, F., Semple, S., Chen, R., & Seaton, A. (2000). Neurological deficits in solvent-exposed painters: a syndrome including impaired colour vision, cognitive defects, tremor and loss of vibration sensation. *Quarterly Journal of Medicine*, 93(10), 655-61.

Donderi, D. C. (1994). Visual acuity, color vision, and visual search performance at sea. *Human Factors*, 36(1), 129-144.

Doorschot PC, Kappers AM, Koenderink JJ. (2001). The combined influence of binocular disparity and shading on pictorial shape. *Perception & Psychophysics*, 63, 1038-47.

Draeger, J., & Schwartz, R. (1989). Experimental tests on the minimal visual acuity required for safe air crew and air control personnel performance. *AGARD Conference Proceedings No. 478. Situational Awareness in Aerospace Operations* (Copenhagen, Denmark, pp. 1-3).

Drance, S. M., Berry, V., & Hughes, A. (1967). Studies on the effect of age and individual prediction. *American Journal of Ophthalmology*, 51, 1262-8.

Drury, C. G. (2001) Human factors good practices in borescope inspection. Retrieved July 8, 2002 on http://hfskyway.gov.

#Drury, Prabhu, & Gramapadhye, (1990).

Evans, D. W. & Ginsburg, A. P. (1985) Contrast sensitivity predicts age-related differences in highway-sign discriminability. *Human Factors*, 27, 637-642.

Fleury, M., & Bard, C. (1990). [Metabolic fatigue and the performance of visual tasks]. *Canadian Journal of Sport Science*, 15(1), 43-50. [Article in French.]

Fukuzumi, S., Yamazaki, T., Kamijo, K., & Hayashi, Y. (1998). Physiological and psychological evaluation for visual display colour readability: a visual evoked potential study and a subjective evaluation study. *Ergonomics*, 41(1), 89-108.

Gegenfurtner, K.R. & Rieger, J. (2000). Sensory and cognitive contributions of color to the recognition of natural scenes. *Current Biology*, 10(13), 805-808.

Gobba, F. & Cavalleri, A. (2000). Evolution of color vision loss induced by occupational exposure to chemicals. *Neurotoxicology*, 21, 777-781.

Good, G. W., Weaver, J. L., & Augsburger, A. R. (1996). Determination and application of vision standards in industry. *American Journal of Industrial Medicine*, 30(5), 633-630.

Goranson, U. F. & Rogers, J. T. (1983) Elements of damage tolerance verification. *12th Symposium of International Commercial Aeronautical Fatigue*.

Ginsburg, A., Easterly, J., & Evans, D. (1983a). Contrast sensitivity predicts target detection field performance of pilots. *Proceedings of the Aeronautical Medical Association*, Alexandria, VA: Aerospace Medical Association.

Ginsburg, A., Evans, D., Sekuler, R. & Harp, S.A. (1982). Contrast sensitivity predicts pilots' performance in aircraft simulators. *American Journal of Physiological Optics*, 59(1), 105-109.

Good, G. W. & Augsburger, A. R. (1987). Uncorrected visual acuity standards for police applicants. *Journal of Police Science and Administration*, 15(1), 18-23.

Good, G. W., & Maisel, S. C. (1998). Setting an uncorrected visual acuity standard for police officer applicants. *Journal of Applied Psychology*, 83(5), 817-824.

Gramopadhye, A. K. & Kelkar, K. (1999) Analysis of shift change in the aircraft maintenance environment: Findings and recommendations. Human Factors in Aviaiton Maintenance and Inspection Research Reports: Phase IX Progress Report.

Gramopadhye, A. K., Drury, C. G., & Sharit, J. (1997). Feedback strategies for visual search in airframe structural inspection. *International Journal of Industrial Ergonomics*, 19(5), 333-44.

Grand Junction, CO. (n.d.) Firefighter, Minimum qualification requirements. Retrieved July 8, 2002 from http://www.gjcity.org/CityDeptWebPages/AdministrativeServices/HumanResources/PDF/Documents/Microsoft%20Word%20-%20FIREFIGHTER%20MIN%20QUAL.pdf

Grimson, J. M., Schalhorn, S. C., & Kaupp, S. E. (2002). Contrast sensitivity: Establishing normative data for use in screening prospective naval pilots. *Aviation, Space and Environmental Medicine*, 73(1), 28-35.

Haymes, S. A., Johnston, A. W. & Heyes, A. D. (2002). Relationship between vision impairment and ability to perform activities of daily living. *Ophthalmic & Physiological Optics*, 22, 79-91.

Hellier, C. J. (2001) *Handbook of Nondestructive Evaluation*. New York: McGraw-Hill.

Hess, R. F., & McCarthy, J. (1994). Topological disorder in peripheral vision. *Visual Neuroscience*, 11(5), 1033-6.

Hills, B. L. (1975). Some studies of movement perception, age, and accidents. Report SR137, Department of the Environment, TRRL, Crowthorne, Berkshire, UK.

Ho, G., Scialfa, C. T., Caird, J. K., & Graw, T. (2001). Visual search for traffic signs: The effects of clutter, luminance and aging. *Human Factors*, 43(2), 194-207.

Holden, R. N. (1984). Vision standards for law enforcement: A descriptive study. *Journal of Police Science and Administration*, 12, 125-129.

Hovis, J. K., & Oliphant, D. (2000). A lantern color vision test for the rail industry. *American Journal of Industrial Medicine*, 38(6), 681-96.

Iserson, K. V. (2001). Color blindness and health care personnel. *Archives of Internal Medicine*, 161(18), 2265-2266.

Johnson, C. A., & Keltner, J. L. (1983). Incidence of visual field loss in 20,000 eyes and its relationship to driving performance. *Archives of Ophthalmology*, 101(3), 371-5.

Johnston, D. M. (1965). Search performance as a function of peripheral acuity. *Human Factors*, 7(6), 527-35.

Kaufman, L. (1974) *Sight and mind: An introduction to visual perception*. Oxford University Press.

Kennedy, A. (1989). Vision testing and microelectronics. *Occupational Health*, 41(8), 222-223.

Kennedy, A., Brysbaert, M., & Murray, W. S. (1998). The effects of intermittent illumination on a visual inspection task. *Quarterly Journal of Experimental Psychology A*, 51(1), 135-51.

Kilburn, K. H. (2000). Indoor air effects after building renovation and in manufactured homes. American Journal of Science, 320, 249-254.

Klein, B. E., Klein, R., Lee, K. E., & Cruickshanks, K. J. (1999). Associations of performance-based and self-reported measures of visual function. The Beaver Dam eye study. *Ophthalmic Epidemiology*, 6(1), 49-60.

Kleven, S. & Hyvärined, L. (1999). Vision testing requirements for industry. Retrieved April 17, 2002, from the American Society for Nondestructive Testing web site: http://www.asnt.org/publications/materialseval/basics/aug99basics/aug99basics.htm

Kline, D. W., Buck, K., Sell, Y., Bolan, T. L., & Dewar, R. E. (1999). Older observers' tolerance of optical blur: Age differences in the identification of defocused text signs. *Human Factors*, 41, 356-364.

Knoblauch, K., Arditi, A., & Szlyk, J. (1991). Effects of chromatic and luminance contrast on reading. *Journal of the Optical Society of America A*, 8(2), 428-39.

Kundel, H. L., Nodine, C. F., & Toto, L. (1991). Searching for lung nodules: The guidance of visual scanning. *Investigative Radiology*, 26(9), 777-81.

Lambert, A., Spencer, M., & Hockey, R. (1991). Peripheral visual changes and spatial attention. *Acta Psychologia*, 76(2), 149-63. Erratum in: (1992), 79(1), 97.

Latham, K., & Whitaker, D. (1996). A comparison of word recognition and reading performance in foveal and peripheral vision. *Vision Research*, 36(17), 2665-74.

Leach, J., & Morris, P. E. (1998). Cognitive factors in the close visual and magnetic particle inspection of welds underwater. *Human Factors*, 40(2), 187-97.

Leachtenauer, J. C. (1978). Peripheral acuity and photointerpretation performance. *Human Factors*, 20(5), 537-51.

Legge, G. E., Parish, D. H., Luebker, A., & Wurm, L. H. (1990). Psychophysics of reading. XI. Comparing color contrast and luminance contrast. *Journal of the Optical Society of America A*, 7(10), 2002-10.

Long, G. M. & Garvey, P. M. (1988). The effects of target wavelenth on dynamic visual acuity under photopic and scotopic viewing. *Human Factors*, 30, 3-13.

Mannan, S., Ruddock, K. H., & Wooding, D. S. (1995). Automatic control of saccadic eye movements made in visual inspection of briefly presented 2-D images. *Spatial Vision*, 9(3), 363-86.

Martin, P. R., Lee, B. B., White, A. J., Solomon, S. G., & Ruttiger, L. (2001). Chromatic sensitivity of ganglion cells in the peripheral primate retina. *Nature*, 410(6831), 933-6. Comment in: Nature, 2001, 410(6831):886-887.

McGwin G Jr, Chapman V, Owsley C. (2000). Visual risk factors for driving difficulty among older drivers. Accident Analysis & Prevention, 32, 735-44.

MED-TOX Health Services (1989). Validation vision standards for Montgomery County, Maryland. MED-TOX Technical Report 2832.

MED-TOX Health Services. (n.d.) Establishing occupational vision requirements for correctional officers. Retrieved February 11, 2002, from http://home.earthlink.net/~medtox/correct.html

Mertens, H. W. (1990). Validity of color vision tests for air traffic control specialist. Report No. DOT/FAA/AM-90/9. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine.

Mertens, H. W. & Milburn, N. J. (1992). Performance of Color-Dependent Tasks of ATCSs as a Function of Type and Degree of Color Vision Deficiency . Report No. DOT/FAA/AM-92/28. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine.

Mertens, H. W. & Milburn, N. J. (1992). Validity of color vision tests for air traffic control specialist. Report No. DOT/FAA/AM-92/29. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine.

Mertens, H. W. & Milburn, N. J. (1996). Performance of color-dependent air traffic control tasks as a function of color vision deficiency. *Aviation, Space, and Environmental Medicine*, 76, 919-927.

Mertens, H. W, Milburn, N. J & Collins, W. E. (2000). Practical color vision tests for air traffic control applicants: en route center and terminal facilities. *Aviation Space & Environmental Medicine*, 71, 1210-1217.

#MILSTD-410

Miyao, M., Hacisalihzade, S. S., Allen, J. S., & Stark, L. W. (1989). Effects of VDT resolution on visual fatigue and readability: an eye movement approach. *Ergonomics*, 32(6), 603-14.

Mon-Williams, M., Tresilian, J. R., Strang, N. C., Kochhar, P., & Wann, J. P. (1998). Improving vision: neural compensation for optical defocus. *Proceedings of the Royal Society of London B: Biological Sciences*, 265(1390), 71-7.

Mullen, K. T., & Beaudot, W. H. (2002). Comparison of color and luminance vision on a global shape discrimination task. *Vision Research*, 42(5), 565-75.

Nagy, A. L., Sanchez, R. R., & Hughes, T. C. (1990). Visual search for color differences with foveal and peripheral vision. *Journal of the Optical Society of America A*, 7(10), 1995-2001.

Nagy, A. L., & Wolf, S. (1993). Red-green color discrimination in peripheral vision. *Vision Research*, 33(2), 235-42.

Nakagawara, V. B., Coffey, J. D., & Montgomery, R. W. (1996). Ophthalmic requirements and considerations for the en route air traffic control specialist: An ergonomic analysis of the visual work environment. DOT/FAA/AM-96/12, Washington, D.C.: U. S. Department of Transportation.

Nakajima, Y., & Kawamura, S. (1998). Redundancy gain in discrimination of colored lights: effects of complexity and eccentricity. *Perceptual and Motor Skills*, 86(2), 691-7.

National Aeronautics and Space Administration. (2002). Astronaut selection and training. Retrieved July 25, 2002 from the NASA Human Space Flight Web site: http://spaceflight.nasa.gov/shuttle/reference/factsheets/asseltrn.html

National Aeronautics and Space Administration. (n.d.). Vacancy announcement for mission specialists and pilot astronaut candidates. Retrieved July 23, 2002 from the NASA Astronaut Selection Web page: http://www.nasajobs.nasa.gov/astronauts/broch00.htm

National Research Council, Committee on Vision. (1985). *Emergent techniques for the assessment of visual performance.* Washington D.C.: National Academy Press.

#NAVSEA 250-1500

Nazir, T. A. (1992). Effects of lateral masking and spatial precueing on gap-resolution in central and peripheral vision. *Vision Research*, 32(4), 771-7.

New York State Parks. (n.d.). Year 2002, Lifeguard qualifications. Retrieved July 15, 2002 from http://nysparks.state.ny.us/lifeguard/qualifications.htm

Niemann, T., Lappe, M., & Hoffmann, K. P. (1996). Visual inspection of three-dimensional objects by human observers. *Perception*, 25(9), 1027-42.

North, R. V. (1985). The relationship between the extent of visual field and driving performance--a review. *Ophthalmic Physiological Optics*, 5(2), 205-10.

Owsley, C., & McGwin, G. Jr. (1999). Vision impairment and driving. *Survey of Ophthalmology*, 43(6), 535-50.

Padgett, V. R. (1989). Summary of empirical validation of firefighter vision requirements: four field experiments. Paper presented at the International Personnel Management Association Assessment Council 13th Annual Conference held in Orlando, FL. Retrieved July 11, 2002, from http://home.earthlink.net/~medtox/firevis.html

Paskiewicz, F. P. (2001) Qualification standards for nondestructive testing (NDT) inspection/evaluation personnel. Memorandum. Retrieved July 15, 2002, from the Federal Aviation Administration Web site: http://www.faa.gov/certification/aircraft/NDTQUALSTDMEMO.htm

Parasuraman, R., Greenwood, P. M., & Alexander, G. E. (2000). Alzheimer disease constricts the dynamic range of spatial attention in visual search. *Neuropsychologia*, 38(8), 1126-35.

Pastoor, S. (1990). Legibility and subjective preference for color combinations in text. *Human Factors*, 32(2), 157-71.

Peters, T. (1980). [Visual requirements of work on data display terminals] *Zentralbl. Arbeitsmed. Arbeitsschutz Prophyl. Ergonomie*, 30(4), 94-9. [German. No abstract available.]

Reiss, M. J., Labowitz, D. A., Forman, S., & Wormse, G. P. (2001). Impact of color blindness on recognition of blood in body fluids. *Archives of Internal Medicine*, 161(3), 461-465.

Riggs, L. A. (1965). Visual acuity. In C. H. Graham (Ed.), *Vision and Visual Perception* (pp. 321-49). New York: Wiley.

Rohaly AM, Ahumada AJ Jr, Watson AB. (1997). Object detection in natural backgrounds predicted by discrimination performance and models. Vision Research, 37, 3225-35.

Ross, D.S. (1978). Colour vision testing in industry: A survey. *Occupational Health*, 30, 479-481.

Rovamo, J. (1983). Cortical magnification factor and contrast sensitivity to luminance-modulated chromatic gratings. *Acta Physiologia Scandinavica*, 119(4), 365-71.

San Diego Police Department. (n.d.). Police officer testing and selection process. Retrieved July 8, 2002 from http://www.sannet.gov/police/join/selection.shtml

Schiefer, U., Hofer, R., Vischer, P. M., & Wilhelm, H. (2000) [Perimetry findings and driving performance. "How much visual field" does a motorist need?] *Ophthalmologe*, 97, 491-497.

Schiff, W. (1980). *Perception: An applied approach*. Houghton Mifflin Company.

Schlingensiepen, K. H., Campbell, F. W., Legge, G. E., & Walke, T. D. (1986). The importance of eye movements in the analysis of simple patterns. *Vision Research*, 26(7), 1111-7.

Schmidt, R.F. (1980) *Fundamentals of Sensory Physiology*. New York: Springer-Verlag.

Scott, I. U., Feuer, W. J., & Jacko, J. A. (2002). Impact of visual function on computer task accuracy and reaction time in a cohort of patients with age-related macular degeneration. *American Journal of Ophthalmology*, 133, 350-357.

Sekuler, R. & Blake, R. (1990). *Perception*. 3rd ed. McGraw-Hill, Inc.

Sekuler, R., Kline, D., & Dismukes, K. (Eds.). (1982) *Aging and human visual function*. New York: Alan Liss, Inc.

Semple, S., Dick, F., Osborne, A., Cherrie, J. W., Soutar, A., Seaton, A., & Haites, N. (2000). Impairment of colour vision in workers exposed to organic solvents. *Occupational and Environmental Medicine*, 57(9), 582-7.

Sheedy, J. E. (1980). Police vision standards. *Journal of Police Science and Administration*, 8(3), 275-285.

Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision*, 14(1), 59-75.

Simeonova, B., & Vassilev, A. (1985). Perception of line orientation in the center and periphery of the visual field. *Acta Physiologica et Pharmacologica Bulgaricae*, 11(2), 3-10.

Sivak, B., & MacKenzie, C. L. (1990). Integration of visual information and motor output in reaching and grasping: the contributions of peripheral and central vision. *Neuropsychologia*, 28(10), 1095-116.

Slade SV, Dunne MC, Miles JN. (2002). The influence of high contrast acuity and normalised low contrast acuity upon self-reported situation avoidance and driving crashes. Ophthalmic & Physiological Optics, 22, 1-9.

Sturr, J. F., Kline, G. E., & Taub, H. A. (1990). Performance of young and older drivers on a static acuity test under photopic and mesopic luminance conditions. *Human Factors*, 32(1), 1-8.

Taylor, W. O. (1975). Practical problems of defective colour vision. *Practitioner*, 214(1283), 654-660.

Tiffin, J. (1952). *Industrial Psychology* (3rd ed.). New York: Prentice-Hall.

Travis, D. S., Bowles, S., Seton, J., & Peppe, R. (1990). Reading from color displays: a psychophysical model. *Human Factors*, 32(2), 147-56

Tredici, T. J., Mims, J. L., & Culver, J. F. (1972). History, rationale, and verification of color vision standards and testing in the United States Air Force. *AGARD Colour Vision Requirements in Different Operational Roles* (sections A4.1-A4.10).

Ungar, P. (1971). Sight at work. *Work Study*, 46-8.

U. S. Air Force. (2001, May 22). Medical examinations and standards. *Air Force Instruction 48-123*. Washington, D.C.: Air Force Departmental Publishing Office.

U. S. Air Force Academy. (n.d.). Pilot/Navigator requirements, Vision requirements. Retrieved February 20, 2002, from http://www.academyadmissions.com/admissions/eligibility/med_eligibility/pilot_navigator.htm

U. S. Coast Guard. (1988). Physical standards and examination. *Coast Guard Personnel Manual* (COMDTINST M1000.6A). Retrieved March 21, 2002 from http://www.uscg.mil/hq/g-w/g-wp/g-wpm/PersMan/PERSMAN%20Opening.pdf

U. S. Coast Guard. (n.d.). Medical examination techniques and lab testing standards: Ocular motility. *Coast Guard Medical Manual* (Chap. 3, sect. C, p. 29). Retrieved February 18, 2002, from http://www.uscg.mil/HQ/G-W/G-WK/G-WKH/G-WKH-1/PUBS/MedicalManual/Chap3-CH17.pdf

U. S. Coast Guard. (n.d.). Physical requirements for mariners. *Marine Safety Manual III - Marine Personnel*. Retrieved March 5, 2002, from http://www.uscg.mil/hq/g-m/nmc/pubs/msm/v3/c4.pdf

U.S. Department of the Interior. (2002). Federal interagency wildland firefighter medical qualification standards. Retrieved July 8, 2002, from http://medical.smis.doi.gov/NIFCMedicalstds.htm

U. S. Department of the Navy, Bureau of Medicine and Surgery. (1996). Vision standards for aircrew maintenance personnel. BUMED Notice 6490. Retrieved July 15, 2002, from https://pma202.navair.navy.mil/ nvg/messages/r090810z.html. Retrievable from http://216.239.33.100/search?q=cache:bj-IYFCbmEAC:https://pma202.navair.navy.mil/nvg/messages/r090810z.html+bumednote+6490&hl=en&ie=UTF-8

U. S. Department of Transportation, Federal Aviation Agency. (1996). Airmen: Medical standards and certification: Eye. *Electronic Code of Federal Regulations* (title 14, chapt.

I, part 67, sections .103(c), .203(c) & .303(c)). Retrieved February 22, 2002, from http://www.access.gpo.gov/nara/cfr/cfrhtml_00/Title_14/14cfr67_00.html

U. S. Department of Transportation, Federal Aviation Agency (1997) Visual Inspection for Aircraft [Advisory circular]. DOT/FAA/AC 43-204, Washington, D.C.: U. S Department of Transportation.

U. S. Department of Transportation, Federal Aviation Agency. (n.d.). Bibliographic guide to publications in aerospace medicine and other related topics. Retrieved on September 27, 2002 from http://www.faa.gov/avr/AAM/BIB.HTM.

U. S. Department of Transportation, Federal Highway Administration. (2001, January). Bridge study analyzes accuracy of visual inspections. *FOCUS*. Retrieved from http://www.tfhrc.gov/focus/jan01/bridge_st_dy.htm

U. S. Department of Transportation, Federal Motor Carrier Safety Administration. (n.d.). Medical advisory criteria for evaluation under 49 CFR Part 391.41. Retrieved July 2, 2002, from http://www.fmcsa.dot.gov/rulesregs/fmcsr/medical.htm

U. S. Department of Transportation, Federal Motor Carrier Safety Administration. (n.d.). Synthesis of the literature. Retrieved March 21, 2002, from http://www.fmcsa.dot.gov/Pdfs/visual2.pdf

U. S. Department of Transportation, Federal Railroad Administration. (1998). Qualification and certification of locomotive engineers. In *Code of Federal Regulations* 49CFR240 (Electronic version, pp. 453-494).

U. S. Department of Transportation, Federal Railroad Administration. (1998). Safety Advisory SA-98-1 (Electronic version).

U. S. Office of Personnel Management. (2001). Qualification standards for GS-2152: Air traffic control series. *Operating manual for qualification standards for general schedule positions* (Electronic version, p. IV-B-272).

VanAssche, C. and Eull, N. (1998) A&P Mechanics performing NDT inspections. Airworthiness Quarterly News Release, 8 (4). Retrieved July 17, 2002, from http://www.awp.faa.gov/new/fsdo/release/long1098.htm

Virginia State Police. (n.d.). Virginia state police trooper law enforcement officer II. Retrieved July 8, 2002 from http://www.vsp.state.va.us/jobtrooper.html

Washington State Department of Personnel. (n.d.). Specification for class of lifeguard2. Retrieved July 15, 2002 from http://hr.dop.wa.gov/lib/hrdr/specs/90000/97420.htm.

West SK, Rubin GS, Broman AT, Munoz B, Bandeen-Roche K, Turano K. (2002). How does visual impairment affect performance on tasks of everyday life? The SEE Project. Salisbury Eye Evaluation. Archives of Ophthalmology, 120, 774-80.

Westheimer, G. (1975). Visual acuity and hyperacuity. *Investigative Ophthalmology*, 14, 570-572.

Westheimer, G. (1987). Visual acuity. In *Adler's Physiology of the Eye. Clinical Application* (8th ed., chapt. 17, pp. 415-28). , St. Louis, MO: C. V. Mosby Co.

Westheimer, G. (2001). Is peripheral visual acuity susceptible to perceptual learning in the adult? *Vision Research*, 41(1), 47-52.

Weston, H. C. (1962). *Sight, light, and work* (2nd ed.). London: Lewis.

Watt, S. J., Bradshaw, M. F., & Rushton, S. K. (2000). Field of view affects reaching, not grasping. *Experimental Brain Research*, 135(3), 411-6.

Wolffe, M. (1995). Role of peripheral vision in terms of critical perception--its relevance to the visually impaired. *Ophthalmic Physiological Optics*, 15(5), 471-4.

Wolffsohn, J. S., & Cochran, A. L. (2000). The practical near acuity chart (PNAC) and prediction of visual ability. *Ophthalmic Physiological Optics*, 20(2), 90-7.

Wood, J. M., & Troutbeck, R. (1994). Effect of visual impairment on driving. *Human Factors*, 36(3), 476-87.